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HIGH DENSITY OPTICAL MEMORY DRUM

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-62-791

February 1963

Electronic Technology Laboratory
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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Project No. 4421, Task No. 442104

(Prepared under Contract No. AF33(616)-7995
by The Bendix Corporation,
Eclipse-Pioneer Division,
Teterboro, New Jersey
Author: Dr. W. W. Lee)

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FOREWORD

This report was prepared by the Eclipse-Pioneer Division of the Bendix Corporation, Teterboro, New Jersey on Air Force Contract Nr AF33(616)7995, Project No. 4421 Optical Memory Development. The work was initiated under the direction of Navigation and Guidance Laboratory and concluded under the direction of the Electronic Technology Laboratory, Aeronautical Systems Division, Mr. J. T. Cogan was Project Engineer for the first part of the Project and Mr. Eugene Maupin was the Engineer for the Electronic Technology Laboratory.

The studies presented began in February, 1961 and were concluded in May 1962 and represent effort of the Advanced Electronics Laboratory of the Advanced System and Development Department of the Eclipse-Pioneer Division. Dr. W. W. Lee was the Engineer directly responsible for this project. Dr. D. H. Blauvelt was the Leader of the Advanced Electronics Laboratory during this period.

Although the studies were a group effort, the key Engineers in the field of interest were T. J. Meloro, Optical Design, B. Spieker, Mechanical Design and I. L. Fischer, Electronic Design.

This report is the final report and it concludes the work on Contract AF 33(616)7995.

This report is unclassified.

ABSTRACT

This paper discusses the techniques of manufacture of high density permanent storage devices for digital computers using optical techniques. The application of these techniques is shown in a feasibility model delivered to the Air Force under the subject contract. This memory had a storage capacity of over a million bits and occupied approximately 1/8 cu. ft. The experimental results are given and future plans are outlined.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

FOR THE COMMANDER:

Leonard M. Butsch, Jr.

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Lt Colonel, USAF
Chief, Bionics & Computer Branch
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SECTION 1

INTRODUCTION

This contract represents the reduction to a working model of the optical memory techniques developed by Eclipse-Pioneer. The unit as delivered is a feasibility model showing the application and realization of these principles in laboratory hardware form. Numerous technical problems were encountered in the construction of this device, some of which were corrected in the design of the instrument and some of which did not become apparent until the completion of the unit. Fortunately, this latter class was of a minor nature and although it proved impossible to correct some of these faults in the delivered unit, owing to the time and expense involved in redesigning the main housing, subsequent units in possible future contracts will have these corrections included.

A photograph of the assembled unit is shown in Figure 1 and an exploded view in Figure 2. The outline drawing is given in Figure 3 and a block diagram of the system in Figure 4.

As indicated in the block diagram, (Figure 4) the delivered unit comprises several subsystems and also requires some specialized drum manufacturing equipment to inscribe the information on the drum. Each of these subsystems and the inscription process will be discussed in greater detail below and a comprehensive outline of the investigation will be given. However, in order that the system as a whole may be easily grasped, a reasonably detailed description of the entire unit follows.

Information is inscribed photographically on a glass drum (1-1/2" long by 1" diameter). The drum is illuminated internally by a commercially available light bulb (GE type BSS-6V) which has a coiled filament approximately 1/3 of an inch long mounted midway along the length of the center part somewhat eccentrically to its axis. Because of this eccentricity

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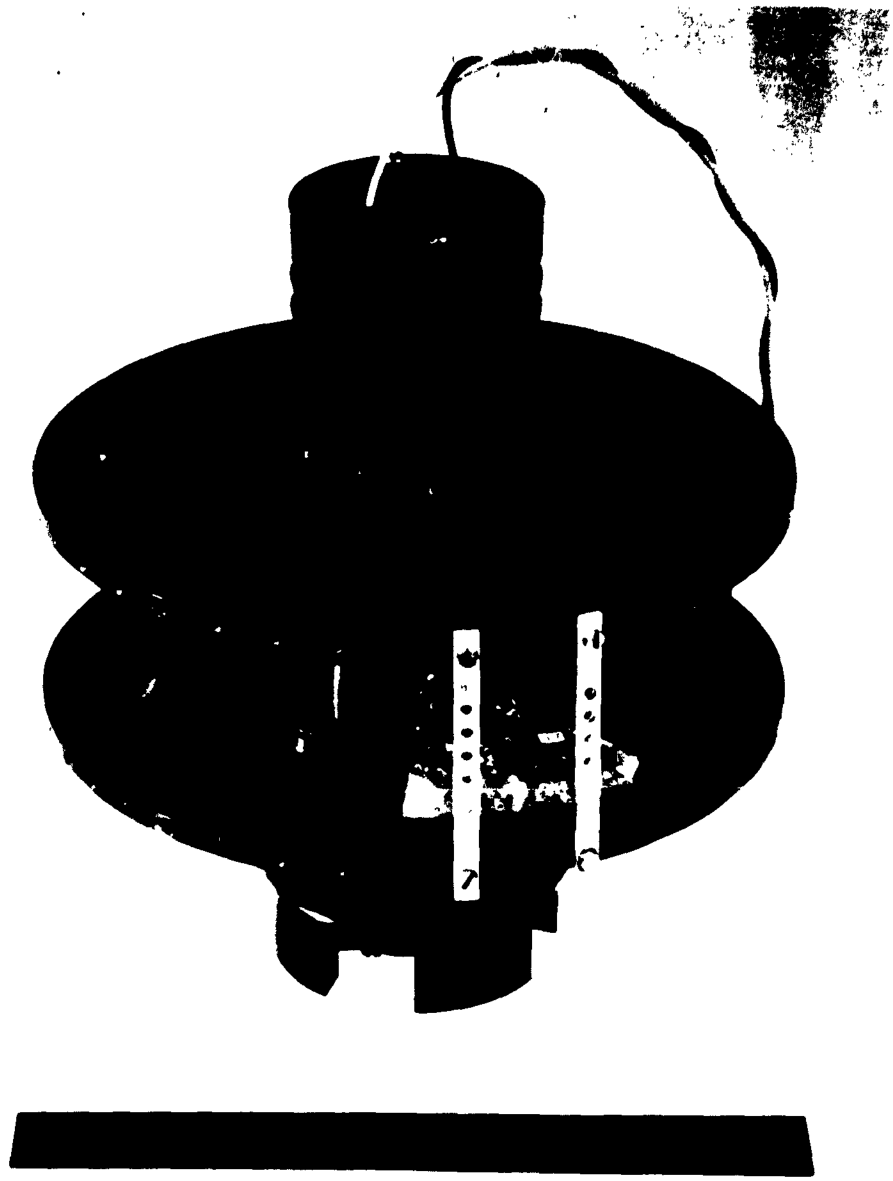
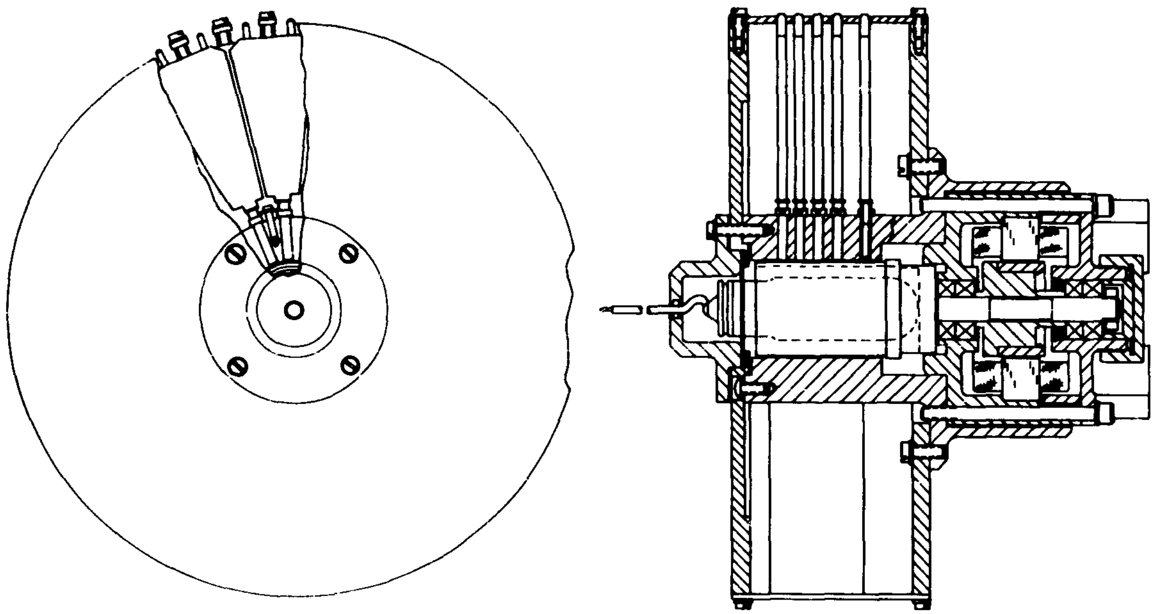


Figure 1 OPTICAL MEMORY STORAGE DRUM

Figure 2 EXPLODED VIEW OPTICAL MEMORY



OUTLINE DRAWING OPTICAL MEMORY

Figure 3

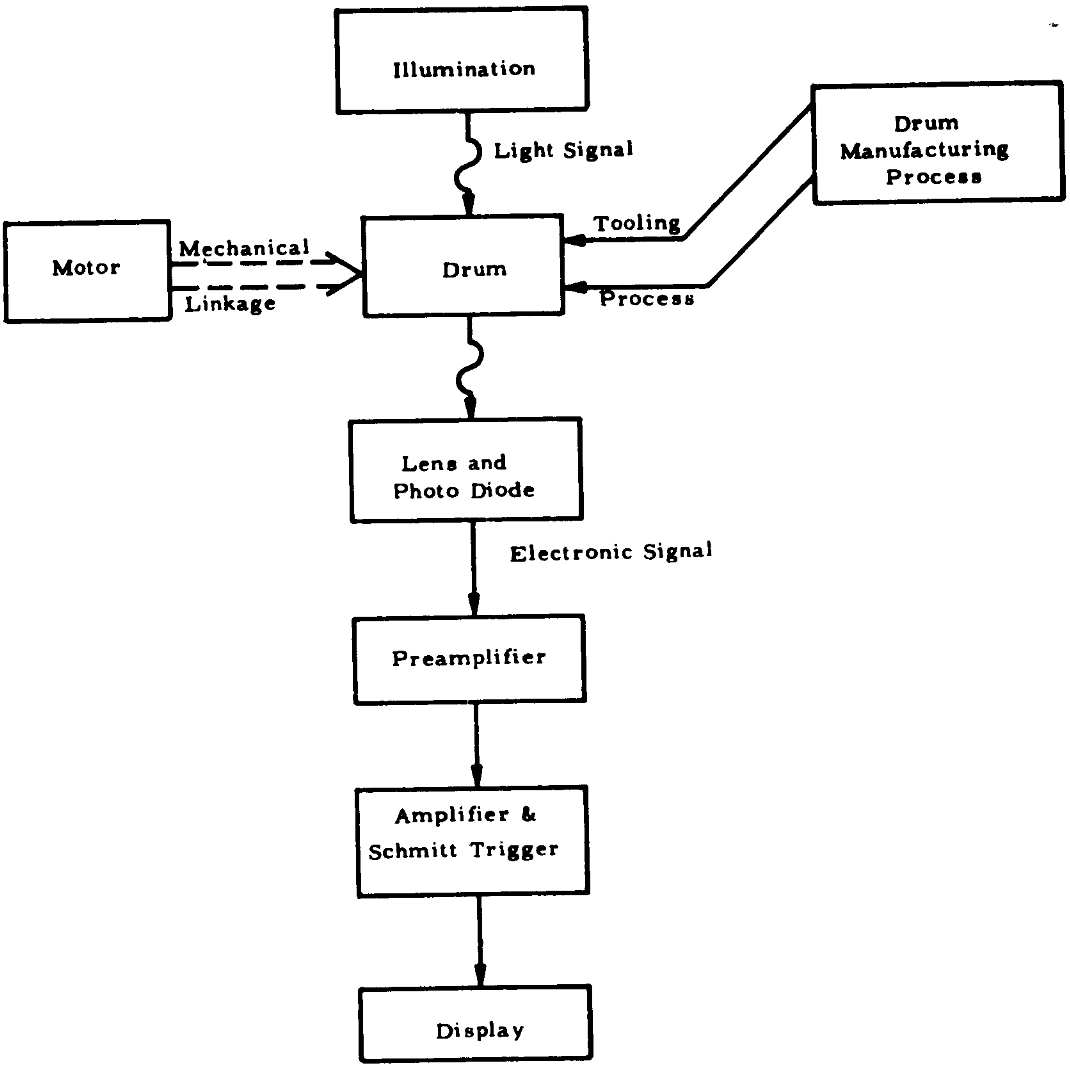


Figure 4 - Block Diagram

of the filament, it is necessary to make provision for adjusting the position of the bulb to give the optimum output on all tracks. The bulb consumes approximately 1 ampere current at 6 volts. The bulb and mounting procedure are shown in Figure 5. Letters A, A indicate the screws which hold the mounting cap in place. When the cap is removed, the bulb may be centered and, upon replacing the cap, the flange on the bulb is held securely by pressure. Power is supplied via the central lead and the other terminal is the chassis ground.

The information is inscribed on a small glass drum using the drum manufacturing apparatus shown in Figure 6. The drum itself is mounted on the indexing head shown in the left of the photograph. This head is capable of rotating the drum in small precise increments, each of which corresponds to 1 bit. The information is furnished in the form of paper tape mounted on the master tape control unit at the center of the photograph. This unit opens and closes small electromagnetically activated shutters in the shutter bank shown at the right hand end of the photograph. After all the shutters (in the shutter bank) are set in the desired arrangement and their arrangement verified, the shutter on the lens mounted on the indexing head is operated. The indexing head then increments the drum one additional bit; the shutters are arranged in a new configuration and the process continues. The time needed for the exposure of a drum comprises approximately one day.

Prior to having the pattern inscribed on it, the drum itself, which is a high precision piece of optical glass as indicated in Figure 7 is coated with Eastman emulsion type #019-14 by the Eastman Kodak Company. It then has the pattern inscribed upon it as described above.

After the inscription of the pattern, the drum is permanently mounted on a hub so that it may be inserted in the motor assembly. Mounting procedure is sufficiently accurate such that the total run out of the drum is less than 1/2 thousandths of an inch.

The drum is then mounted into the motor assembly, Figure 8, where it is held by two pairs of matched pre-loaded ball bearings, one pair at either end of the hub shaft. The motor itself is a

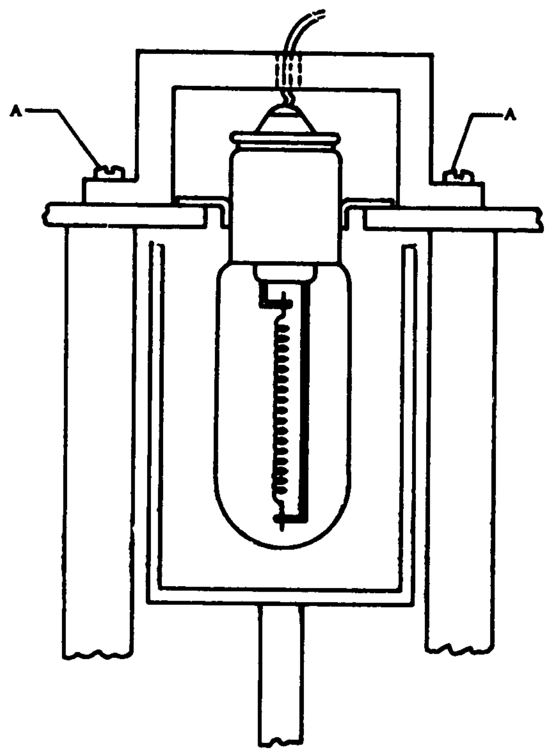


Figure 5 - Illumination Mechanism

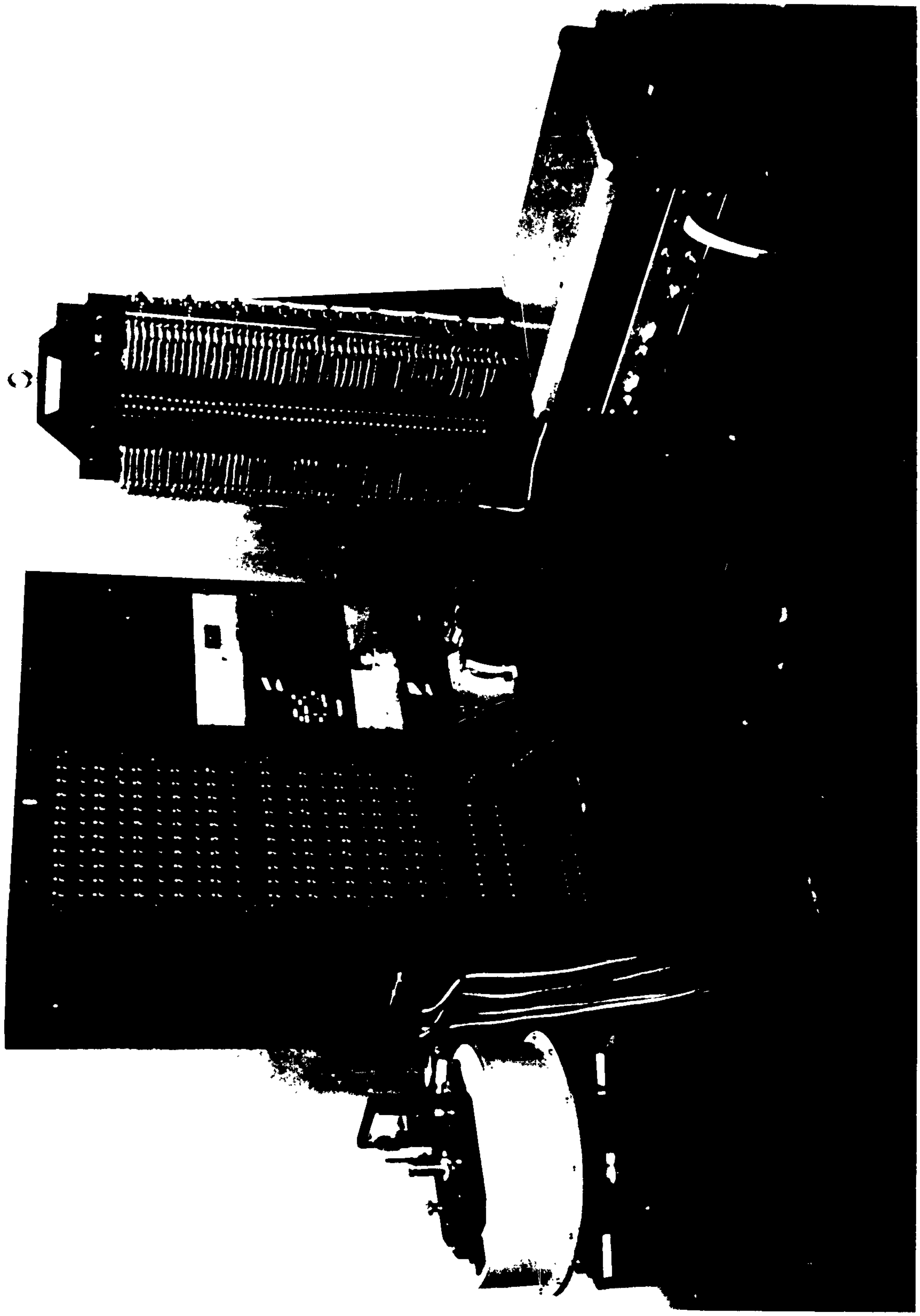


Figure 6 DRUM MANUFACTURING EQUIPMENT

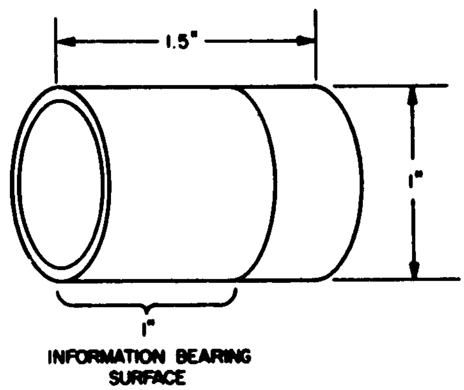


Figure 7 - Glass Drum

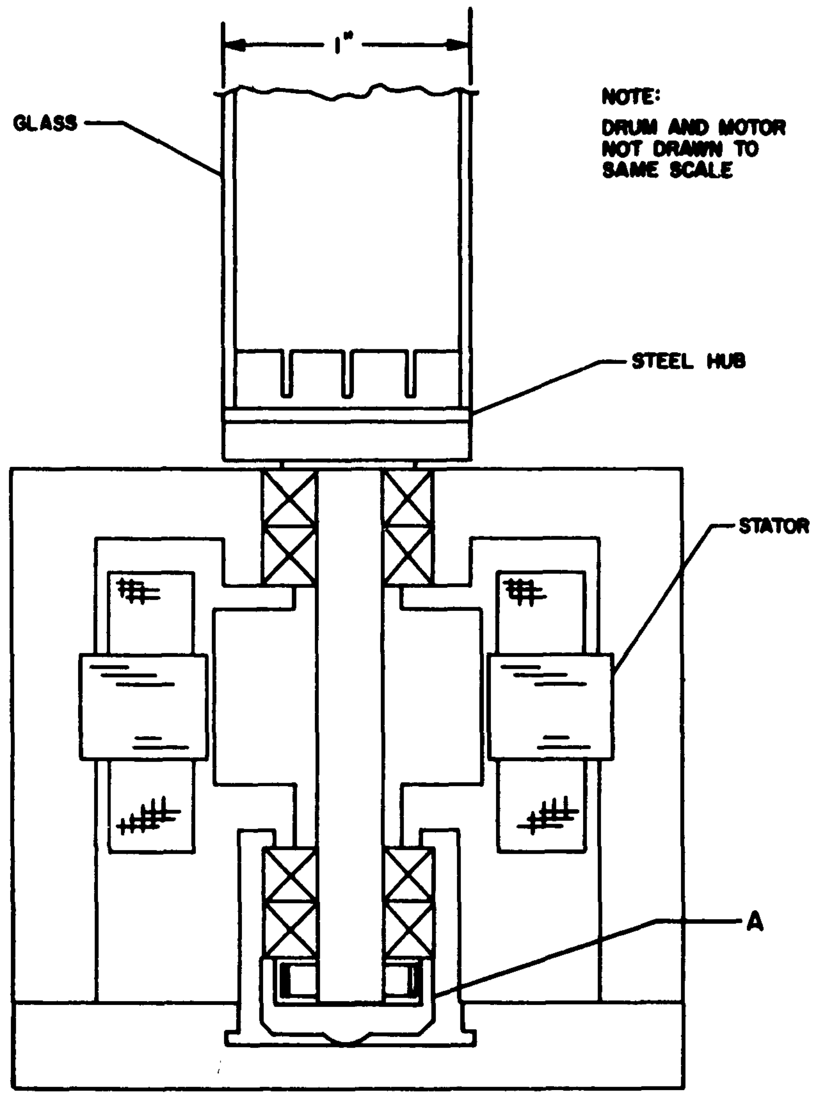


Figure 8 - Motor and Drum Assembly

hysteresis synchronous model using standard wiring and laminations, but having the case designed to be compatible with the rest of the unit. The drum rotation speed is 12,000 RPM.

The information is inscribed on the surface of the drum in NRZ form, each bit being .004" long and .0008" wide. The information is read by read-heads mounted radially to each track. The read-head consists of a sapphire plano-convex lens of 1/2 millimeter focal length, which is pressed into a hole in the flanged mounting tube shown in Figure 9. This tube is shimmed to the proper position by shims placed under the flange. As may be seen from the figure, the lens is mounted eccentrically to the tube. This allows the field of view of each lens to be moved along the track by rotating the tube about its axis. This in turn allows each read-head to be adjusted so that all read-heads will read the beginning of their respective tracks simultaneously.

The tubes are held together in pairs by the clamp and screw arrangement shown in Figure 10. The photodetector and pre-amplifier are built together in a single unit which is shaped as a segment of a circle (Figure 11). The pre-amplifier is mounted on a thin printed circuit board. A nylon sleeve slips over the rear end of the photodetector and is cemented to the board. The entire assembly is then potted with an Epoxy potting compound (PS 269) per Bendix specification. The lens on the front of the diode is ground flat and the diode is inserted into the lens mounting tube. The rear of the pre-amplifier is inserted into a strip type clamp which holds several pre-amplifiers arranged in a line parallel to the axis of the drum.

The circuit of the amplifier is shown in Figure 12. It is a high gain tuned amplifier providing compensation for the frequency deficiency of the photo diode in two ways. First, the RC time constant of the photo diode is reduced by providing a low resistance path in parallel with the photo diode. Second, a peaking coil is placed in the collector circuit of the first stage to provide a sharply tuned circuit to reduce noise.

From this, the signal goes through a low noise cable to a high gain amplifier and then into a Schmitt trigger whose triggering level is adjustable. This allows each track to be adjusted indivi-

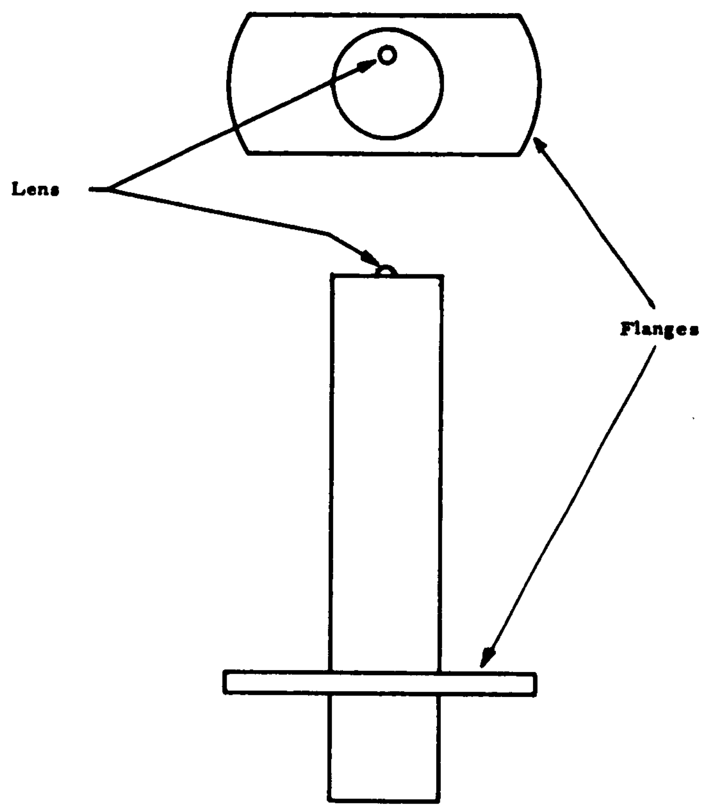


Figure 9 - Lens Mounting Tube

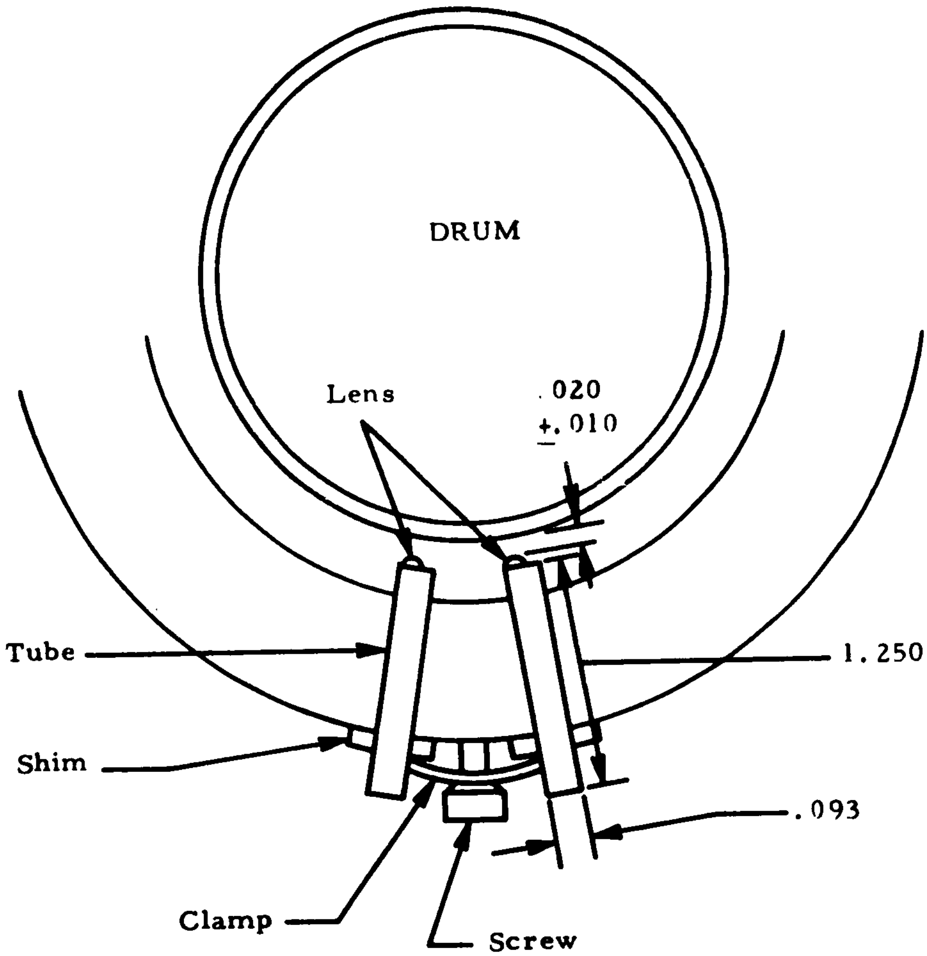


Figure 10 - Mounted Read Head

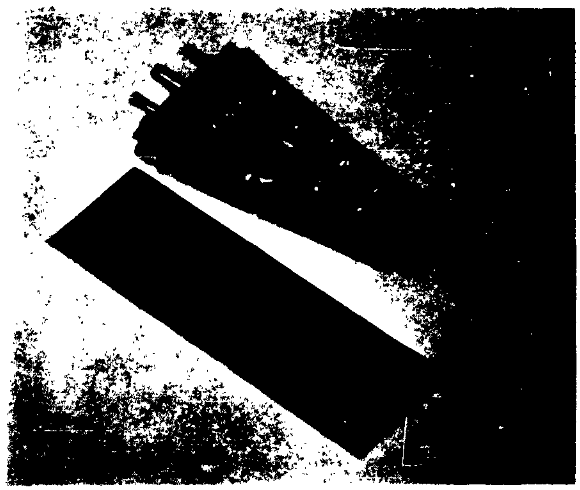


Figure 11 READ OUT PREAMPLIFIER FOR OPTICAL MEMORY

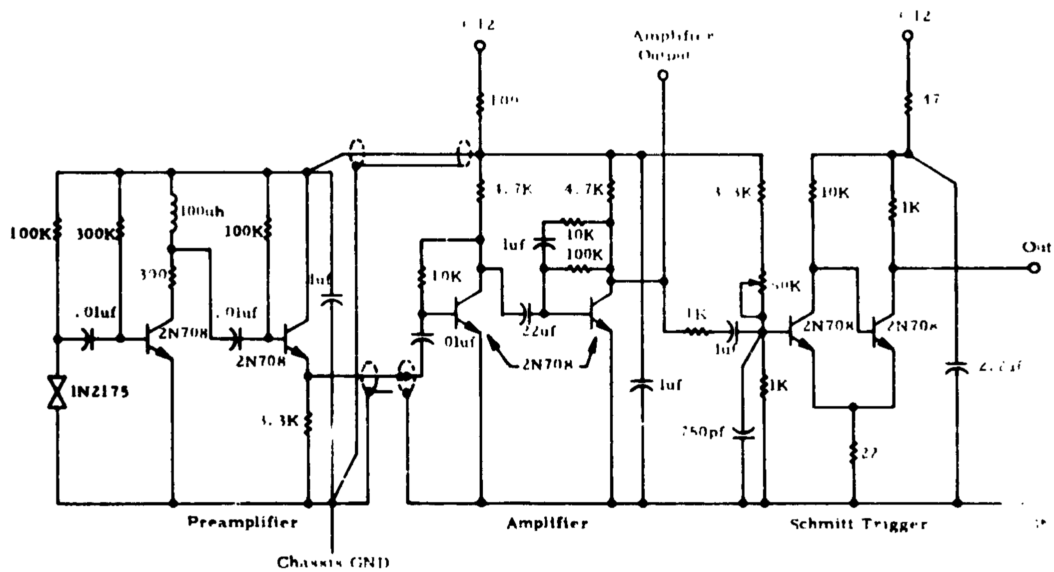


Figure 12 - Optical Memory Readout Electronics

dually according to the signal to noise ratio of each particular track. In addition, display circuitry was provided to allow inspection of each entry along the track. Severe noise problems required careful isolation of power supplies and grounds in order to make this circuitry operable.

SECTION 2

DETAILED DESCRIPTION AND INVESTIGATION HISTORY

2.1 Illumination Subsystem

The bulb actually used in the delivered unit is an incandescent bulb, GE type BSS-6V, commonly used as an exciter lamp in sound films. This bulb has a coiled filament approximately 1/3" long halfway along the length of its axis. The filament is mounted eccentrically to the axis of the lamp and is held in place by a C shaped clamp. Due to the eccentricity of the filament, it is necessary to provide sufficient room in the mounting of the bulb that it may be shifted from side to side in order to insure uniform illumination of all tracks. This is done by providing as a mounting fixture, a hollow flanged cylinder somewhat larger than the bulb, into which it fits. The bulb may be moved freely inside this cylinder until the optimum signal is obtained. The cylinder cover is then screwed down and holds the mounting flange of the bulb by pressure. A wire comes through the central hole of the cover and supplies the necessary power, the return being made through the mounting flange and the chassis of the instrument. The bulb consumes approximately one ampere at 6 volts.

The first light source employed was a much smaller incandescent bulb having a prefocused lens built into the envelope. This was used as a standard throughout the experimental work on the optical memory and is still being so used. This is the TS-4 bulb fabricated by the Tungsol Lamp Company, which produces a spot 1/8" in diameter, 1/4" from the front end of the bulb envelope. The brightness at this point is 1200 foot candles. The power consumed is one watt at 2.5 volts. The bulb itself has a lifetime of 2500 hours and has been vibration tested and is extremely resistant to shock and vibration.

Because of the impossibility of illuminating all tracks with an array of bulbs of this nature inside the drum, due to lack of physical space; several other procedures were investigated as possible means of illuminating the drum interior. Two lucite fixtures, Figures 13a and 13b were built and tested. The light losses were so severe that this proved an impractical approach, as no usable signal was obtained. A simple reflective system was designed and worked well on a single channel, however, it was not possible to provide a simple reflective system for all channels due, again, to the geometrical configuration.

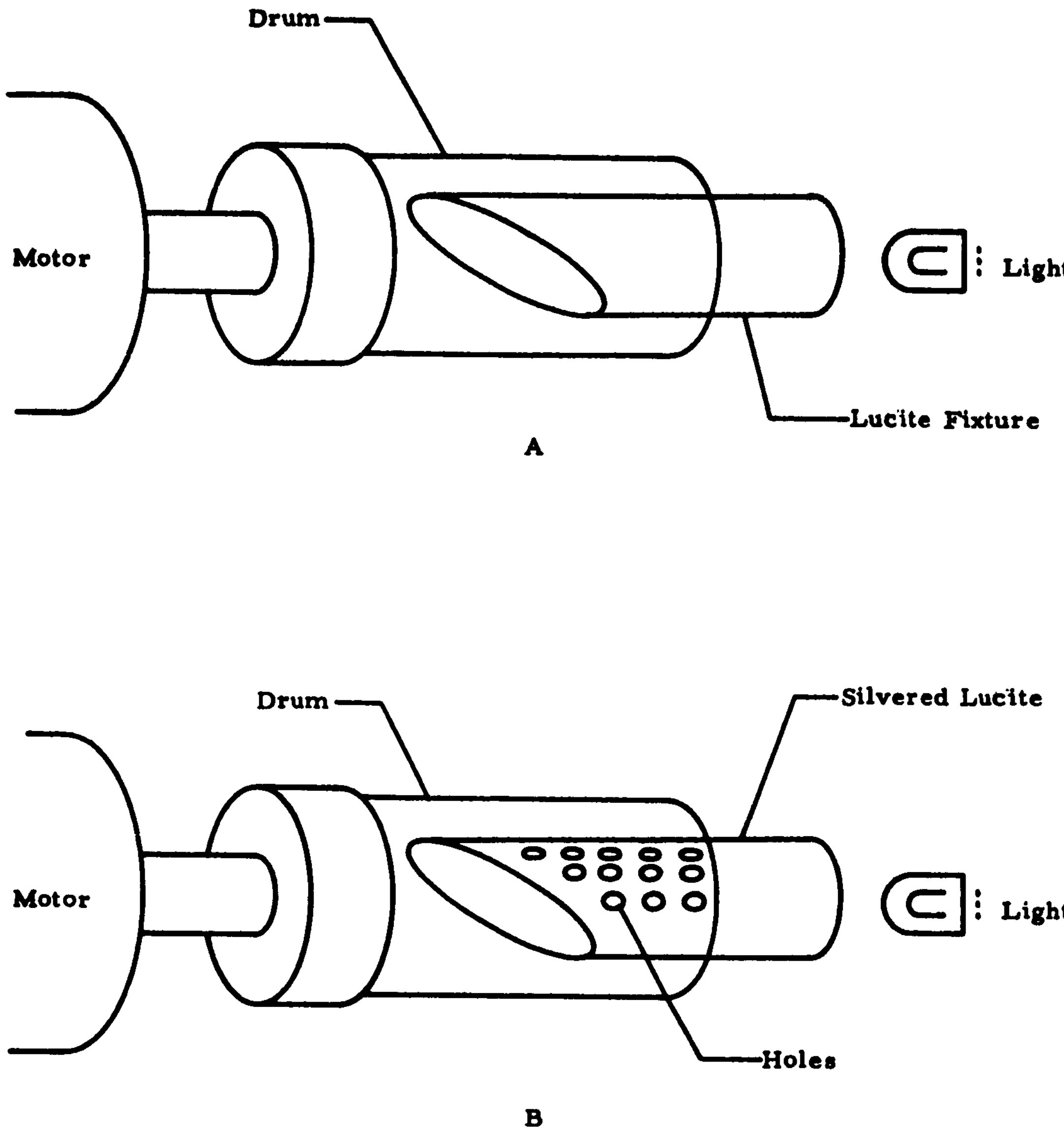


Figure 13 - Lucite Illumination Fixtures

The next approach taken was that of fiber optics. Several fiber optic fixtures of the general nature shown in Figure 14 were built. Light was admitted to one end, made a right angle bend and was emitted at a point opposite the appropriate read heads. The metallic holder was made in several pieces, two semi-cylinders, an end cover and a fiber retaining ring. The fibers were inserted into the holes in the semi-cylinders, were brought up and threaded through the fiber retaining ring and the entire unit was then assembled. The assembled unit was then filled with an epoxy potting compound. It proved necessary to do the filling under vacuum since the first units showed many voids as the high viscosity of the potting compound prevented it from interpenetrating the fiber bundles.

After potting, the fiber fixture was polished. A great deal of difficulty was encountered in the polishing process as the fibers tended to swim in the epoxy, since the epoxy and glass had two different hardnesses giving a differential cutting rate for the polishing compound. This resulted in shattering of the fiber ends. It proved necessary to use a filled epoxy (Emerson and Cummings Stycast #GT2850) whose hardness closely matched the hardness of the glass. In the polishing process, the use of a coarse grit to obtain an approximately smooth surface prior to final polishing was not feasible as the presence of grit particles of the same order of magnitude diameter as the fibers caused severe crushing and splintering of the fibers. It proved necessary to use jewelers rouge and cerium oxide only in the polishing process. The two most satisfactory processes were a low speed polish using a cerium oxide and water slurry and a high speed polishing process using jewelers rouge on a felt pad. Of the two, the high speed process appears to give a somewhat better surface and is preferable because of the much greater speed with which the polishing process is accomplished. The ends of the fibers must have a precision optical polish on them as the spectral region in which the diode is most sensitive is extremely susceptible to diffusion by irregularities in the surface. An adequate polish has been secured when microscopic examination by transmitted light shows clearly the demarcation between the cladding and the fiber body.

Two problems remain. First, the geometry of the fiber piece is not suitable as the single bend in the light fiber results in the emission of a hollow cone of light with a central dark area at the exit pupil of the fiber. Second, the process is one of extreme delicacy and com-

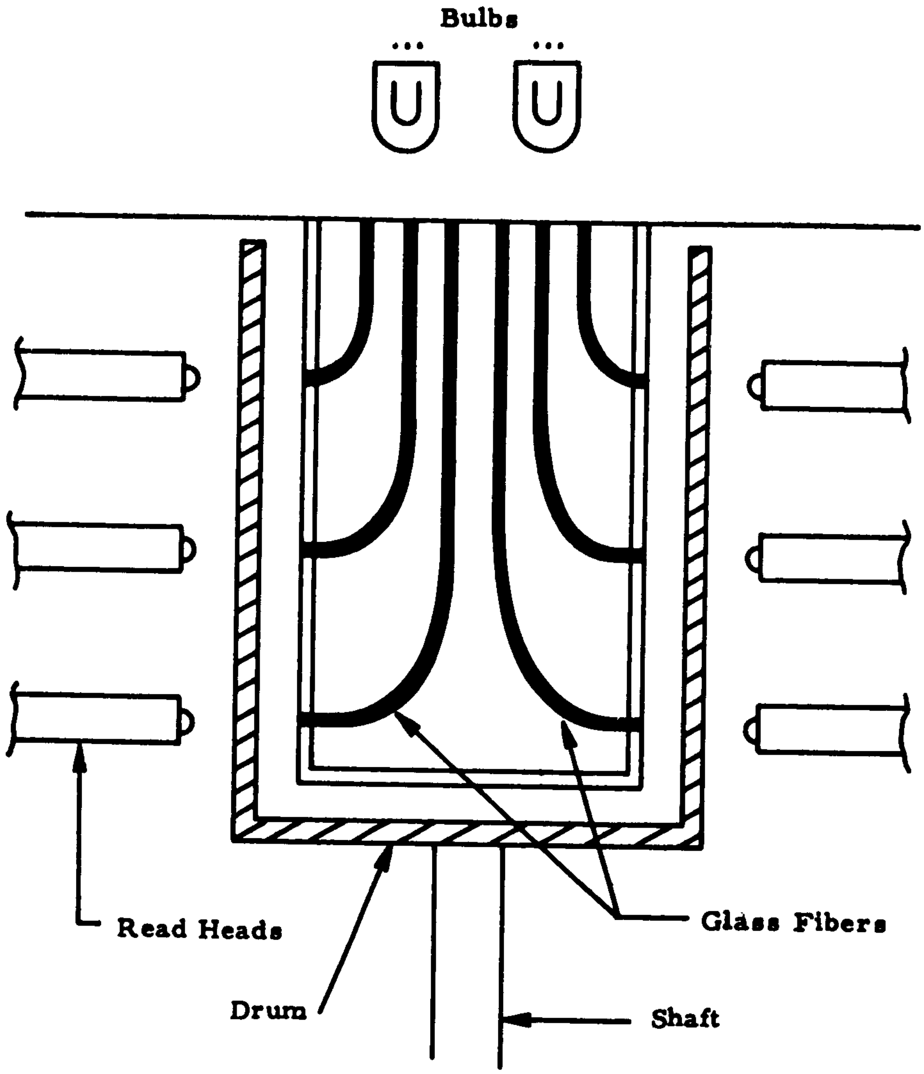


Figure 14 - Fiber Illumination System

plexity; fiber breakage is high, labor time to assemble a fixture is also high. None the less, this does permit easy replacement of the bulb with no critical alignment problems and also is extremely resistant to environmental damage.

Various other types of light sources have been considered including gas discharge tubes, electroluminiscent panels and radio active powered phosphors (Table I). None of these, however, proved to have sufficient intensity to be useful. Future work in this area will be concentrated in the design of more reliable bulbs and the investigation of fiber and reflective optical systems.

2.2 Drum and Drum Manufacturing Process

Information is inscribed on the glass drum photographically. This is done by a combination of a shutter bank and an indexing head, both of which are controlled by a master control unit. The apparatus for drum inscribing is shown in Figure 6. The indexing head and the shutter bank are mounted at opposite ends of a lathe bed in order that precise alignment may be achieved. The whole unit is kept free from vibration and other disturbing forces.

The indexing head consists of a gear train driven by a motor. The gear train provides a 16,384 to 1 reduction which may be changed to 65,536 to 1 by replacement of one gear pass. On the second gear shaft, there is a cam and microswitch arrangement which stops the drive motor one revolution after its activation. As the first gear pass is a four to one reduction this stops the drum at 4096 different stations during its rotation. At each of these stations accuracy is controlled only by the precision of the gears. Measurement indicated that the total cumulative station to station error between any two stations is less than 10% of a bit width. Since all gears are in the same position at the end of a run that they were at the beginning, exact registry and closure are achieved.

The drum is mounted on a spindle behind a 75 millimeter camera lens equipped with a shutter. Experiment has shown that the optimum exposure is 1/25 seconds at F5.6. A dial indicator reading .0001 inches/div. has been provided between the mounting plate of the lens and the body of the indexing head for focusing purposes. The

TABLE I

NON INCANDESCENT LIGHT SOURCES EVALUATION STUDY

Light Source	Results
Sylvania Electroluminiscent Panel	No observable signal or increase in noise level.
NE-2 Type Bulb	Same as above
Daylight Type Fluorescent Tube	Same as above
Gas discharge lamp with phosphor added to increase infrared content.	No usable signal, however, a slight increase in amplitude of noise indicated that this device had better output than those previously mentioned.

(A theoretical calculation of the output of the radio-activated phosphor showed its output to be several orders of magnitude too low for use with a solid state detector.)

allowable depth of field appears to be on the order of 2 thousands of an inch. In order to facilitate focusing, a special device has been made which allows photographic plates to be used instead of the drum so that the accuracy of the set up may be verified.

The shutter bank consists of an array of 128 shutter units, each unit consisting of a shutter leaf, a solenoid and two micro-switches. In front of these is a steel tape containing 128 holes half the size of the shutters. This tape may be moved to cover either all the upper or all the lower halves of the shutter, thus giving 256 tracks along the length of the drum. The two micro-switches are arranged so that when the shutter is open, that is to say, when the solenoid is deenergized and the shutter leaf fully retracted from the optical path, one microswitch is closed and the other open. As soon as the solenoid is energized and the shutter leaves the fully open position, the device is adjusted so that the closed microswitch opens. While the shutter is travelling to the closed position, both microswitches remain open - the second microswitch only closing when the shutter is fully closed. This provides a necessary check against solenoid malfunction or jamming of the shutter.

Behind the shutter is a slit some 30" long with moveable jaws. These jaws are opened to a distance whose magnitude corresponds to the desired bit size multiplied by the reduction of the optical system. Behind this is placed an ordinary daylight type fluorescent tube. This tube is on throughout the entire drum making procedure.

Control of the entire system is provided by the master tape control unit which includes a cam timer. As it is necessary to provide 128 bits of information simultaneously to the shutter bank, it has been necessary to provide a bank of relays to act as a buffer storage device between the paper tape and the shutter bank. Because of this and because of the spiral arrangement of the read heads (see below, Section 2. 5) which offsets the beginning of each successive track 9°, the tape format presents some noteworthy features. The tape is divided into blocks. Each block comprises 128 holes. The information in this block corresponds to the information found in one axial line along the surface of the drum. If the read heads were all arranged in a straight line, the first block would contain the 128 first bits

of each of the 128 tracks. As the read heads are displaced by 9^{o} which corresponds to approximately 100 bits, the first block will contain the first bit of track one, the 101st bit of track 2, the 201st bit of track 3, etc. A computer program has been worked out to enable this tape format to be made up from a number of individual tapes, each of which would correspond to one track, and this formatting process can be done automatically. Two tapes are made up separately as a guarantee against an error in the format of the two tapes.

When the two tapes are complete, they are placed in a pair of tape readers (Tally Type 424P). The first of these tape readers sets the bank of 128 locking relays 5 at a time. As each set of 5 relays is set, it closes the corresponding shutters in the shutter bank. These activate their respective microswitches and the position of the microswitches is verified against the holes in the second tape. Should there be a failure to verify, the entire inscription process is immediately halted.

Upon the completion of the transferral of information from the tape to the shutter bank, a signal is sent to the cam timing device which activates the shutter on the camera lens mounted on the indexing head. The operation of this shutter causes the information to be inscribed on the drum. After the operation of this shutter, the cam timing device then activates the motor in the indexing head advancing the drum to the next position, and causes the tape readers to set in a new block of information. The process is self-repetitive until the inscription of the drum is complete.

It was not immediately obvious that the optimum way to perfrom the inscription operation was photographic. Various other methods were investigated. The first method investigated was that of mechanical inscription of the information on the drum using a single diamond stylus or an array of styli activated by a system of mechanical levers. Investigation of this proved however, that the tolerance build up due to inevitable machining allowances and subsequent wear during the lifetime of the instrument would render the first system unusable. A simple time analysis ruled out the use of a single stylus and both of the tolerance problems would be much more severe in the case of an array of styli.

A second approach investigated was that of inscribing the information photographically on a piece of film and wrapping the film around the corresponding drum. This was rejected because the elasticity of the film might easily lead to skewing or other misalignment of the pattern. The possibility of inscribing the information on a metallic film or screen and then fusing this to the glass was also investigated as this approach would eliminate the elasticity of the film. It was, however, ruled out as being difficult to implement.

Several major changes in the present system are in process, chiefly, to increase reliability. The first change is the replacement of the existing tape readers by a new type of tape reader which will be capable of reading an entire block of information at a time. Each microswitch and solenoid combination in the shutter bank is being replaced by a prism, bulb and photodetector combination so that in place of a mechanical unit, a solid state shutter will be available. This will eliminate the severe reliability problem inherent in a multiple mechanical system. In the indexing head, it has been already proven necessary to replace the original motor which was a stepping type motor with the present cam and synchronous motor unit. It is also planned to incorporate in the unit a large shaft encoder disc with appropriate circuitry so that the indexing head will be a closed loop system.

2.3 Drum and Drum Sensitizing Process

As delivered, the unit contains a small glass drum whose outer surface bears the information. This drum is 1.5" long, 1" in diameter and meets the specifications shown in Figure 7. The drum is made of lime glass polished to best optical finish. It is clear and free of strains, pebbles, and other defects. For the photoprojection method described above, the glass must be sensitized with a photosensitive emulsion. Had the mechanical inscription process been used, no such sensitization would have been necessary. It is coated with Kodak emulsion Type No. 019-14 by the Eastman Kodak Company. This is a microfilm type emulsion capable of high resolution and high contrast. The emulsion coated drum is placed on the indexing head and has the pattern laid down as above. The drum is then removed from the indexing head and developed similarly to an ordinary photographic film.

During the entire process, the drum is not mounted permanently to any hub or holding fixture. It is locked on the spindle by a set of spring fingers which holds it concentrically to .001 inches with the axis of rotation of the spindle. After development of the pattern the drum is placed on its hub in the following manner: the hub is placed in a jig borer and the drum placed on the spring fingers of the hub and a dial indicator placed so as to read the alteration in radial distance as the drum is rotated. The drum is rotated and moved by an arbor that holds the cylinder internally until the dial indicator shows that a minimum run-out has been attained. As will be noted from the figure, the drum is held to the hub by a series of external spring fingers in order to provide a minimum of stress concentrations. No stress concentrations have been observed at these points in polarimeter tests.

Several other alternative methods of sensitizing the drum have been investigated. Three approaches have been investigated. These are respectively - the etched, the photoresist and the photographic.

In the etched method, the drum was first coated with a coat of either vapor deposited or chemically deposited silver or aluminum. This was covered with a photoresist. The pattern was then placed on the surface of the drum by projection as above. The photoresist was developed and the metal etched by a suitable etching. This proved to be unfeasible because the etch ratio resulted in the lifting of the metal film, especially in the case of single isolated bits. If the etching time was decreased to allow better adhesion, the result was imperfect cleansing of the clear space between bits. In as much as this process promised no more than the ordinary photoresists process, work here was temporarily discontinued at this point.

The photoresist method called for coating the drum with a photoresist inscribing the pattern upon it and developing the pattern. The photoresist was then dyed. This process offered, at first glance, many advantages. The photoresist being essentially a grainless material offered a much higher resolution than that obtained with photographic plates. It offered also, much more desirable handling characteristics as it was much less sensitive to minor impurities and did not demand the elaborate coating facilities needed to handle photographic emulsions. Its major advantage, however, was that it left clear spaces between the

line, that is to say, areas of uncoated glass as opposed to the transparent gelatin found in the clear portions of a photographic plate.

Two types of photoresists were evaluated. One was the commercially available Kodak photoresist (KPR) and the other was a proprietary emulsion designated as BPR. Of the two, the BPR appeared superior in that it yielded slightly shorter exposure time and considerably greater opacity. There was also a slight tendency of the KPR to develop imperfectly and uncleanly, leaving a cloudy residue on supposedly clear areas. The exposure time of both of these was long. BPR required 4 seconds and KPR required 6 seconds of exposure. In order to get a sufficient exposure, it was necessary to replace the flourescent tube mentioned in Section 2.2 above with a 36" 4 kilowatt Xenon Arc tube and to provide cooling for the same. This introduced considerable problems in handling the voltages and currents needed to activate this tube. Accordingly, the exposures were made in the following manner: the shutter on the camera lens on the indexing head was left permanently open and the Xenon Arc tube was ignited for the desired length of time by the cam timer. This type of process considerably increased the length of time necessary to make a drum. However, results obtained were satisfactory. Resolution was excellent and contrast proved adequate.

The third area in which investigation was undertaken was that of having the drum coated witn a photographic type emulsion by a vendor. The coating process was in all cases, difficult to implement because of the impossibility of eliminating a gravity gradient across the cylinder. This was especially true of the highly sensitive photographic type emulsion and this remains an operation in which the yield factor is not high. Experience with these emulsions indicated that the maximum line density obtainable was 600 to 800 lines per inch or some 30 lines per millimeter. This is considerably less than the commonly quoted resolution available with this type of emulsion and this difference is attributed to two causes. First, the standard of resolution demanded is extremely high. A clear space must be of the same clarity whether it is one bit wide or 1,000 bits wide, while the usually quoted standards for resolution merely indicate that there is an appreciable change in optical density still to be found at this line density. Secondly, the process of putting the emulsion on the drum appears to have some effect on its resolving power. Sample patterns have been made using the same emulsion coated on microscope slides

and these appear to show a somewhat higher resolution. Also, for some reason, microscopic examination of the drum shows some granulation which is not present on the slides. However, at low density, e.g. line densities below 800 lines per inch, the photographic emulsion works very well and a drum may be made quickly and readily using this emulsion.

The contrast properties of the emulsions are summed up in Table II. As may be seen from this table, although the transparency of a clear area is somewhat lower in the case of the photographic emulsion the overall contrast ratio is superior. Furthermore, as the photographic emulsion is several orders of magnitude faster, not only may a drum be made much more rapidly, but also, the problems associated with the high voltage, high current power supply may be eliminated. For these reasons, it is felt that whenever the bit density is low enough so that it may be used, the photographic emulsion is desirable. As will be seen in the next section, at present, limitation on bit density means that the photographic emulsion is optimum in all present cases.

Future work in this area will include investigation of other types of photoresists and means for improving both the contrast and speed of the two photoresists previously investigated. It is felt that the photoresists offer much greater potential in the long term for future growth. It is not felt that any of the more exotic techniques such as metal etched, thermal developed emulsions, non-developing emulsions, etc. offer sufficient promise at this time to be worthy of full scale investigation, however, a continuing survey is being made of new developments in this field.

2.4 Motor Description

The drum is mounted in a housing using two pairs of matched pre-loaded ball bearings, type no. EP 1302402-1, one pair at either end of the hub shaft. A preload is provided by compression of a wavy washer and height adjustment is provided by means of the nut A in Figure 8. The motor is of the hysteresis-synchronous type in order to eliminate the short lifetime and other maintenance problems associated with brushes and to provide a smaller diameter rotor than that available with the squirrel cage type of motor. The coils of the slug of the rotor are standard Eclipse-Pioneer No. EP 1798019-1 and

TABLE II

NORMALIZED TRANSMISSION OF THREE SENSITIZING AGENTS

Agent	Transmission Clear Area	Transmission Opaque Area	Contrast T_c/T_r
KPR	1.	.9	1.1
BPR	1.	.8	1.25
Photographic	.8	.3	2.6

EP 1786437-1 respectively. The housing, however, is designed to be an integral part of the overall housing and support structure of the unit. The motor housing is a separate sub-assembly and by removing 4 bolts, the motor housing together with the drum may be removed from the unit. While removing the subsystem, care must be taken not to damage the two pilot studs provided or to shatter the drum.

The drum and hub sub-assembly may be removed from the motor by removing the nuts and washers at the bottom of the drum hub shaft, and pressing the drum shaft out through the upper end of the housing. The two lower bearings will remain in the housing, but the two upper bearings may remain on the shaft. Two holes are provided in the base of the hub in order that the upper bearings may be removed from the shaft by use of a special tool, similar to a spanner, which passes through the holes and pushes against the inner race of the bearing. Care must be taken not to pull on the outer race of the ball bearing as this may result in destructive disassembly of the bearing itself. The same set of holes may be used to hold the drum shaft from rotating during the first step (removal of the retaining nut and washer).

The motor is a three phase 400 cycle motor having 4 poles, consequently rotating at 12,000 rpm. Approximate power consumption of the motor is 7 watts. The length of time necessary for the motor to attain full operating speed is approximately 2 seconds.

Several changes are envisioned in the motor design. The drum hub will be made detachable from the drum hub shaft and the entire motor bearing shaft assembly will be sealed. This is a protective measure designed to give longer life to the bearing by eliminating the possibility of dust or grit entering the bearing assembly during drum replacement. A reduction in the power consumption can be obtained by allowing the run up time to increase. It is felt that an increase of several orders of magnitude in the run up time would not be excessive and that a substantial saving in power requirements can be made this way.

2.5 Readout System

The information is inscribed on the surface of a drum in NRZ form, each bit being .004" long and approximately .0008" wide. This gives a total of 256 tracks along the axial length of the drum and 4096

bits per track around the circumference of the drum. Each track has a separate read head and preamplifier provided as a read out system. The read head consists of a cylindrical tube closed at one end, with a pair of ear like flanges near the other end. In the closed end of the tube is mounted a small sapphire lens, (Figure 15). This lens is 1/2 millimeter in diameter and hemispherical in shape. It has a focal length of approximately 1/2 millimeter. These lenses may be obtained from Adolph Mellor, Inc., Providence, Rhode Island. It is pressed and staked into a hole in the closed end of the cylinder in the same manner as that by which a watch bearing is mounted. Extreme care must be taken in mounting the lens in order to avoid fracturing or otherwise damaging the optical surface.

The entire array of read heads is held in the main housing. This housing is cylindrical in shape with a large circular plate at either end of the cylinder. The read heads are slipped into holes arranged in a helix along the surface of the cylinder. Each read head is therefore, displaced angularly from its predecessor by an amount equal to 9 degrees in the delivered unit. This is necessary in order to accommodate the total number of read heads and in turn, necessitates the angular displacement of the tracks mentioned in Section 2.2 above.

Between every other pair of holes, a screw hole is provided which holds a small clamp which fits over the ears of the two adjacent lens holding cylinders holding them firlmy in place.

Several adjustments are provided in the read head itself. As it is impossible due to mechanical tolerances to insure sufficient accuracy in the initial construction of the device so that every read head will read the beginning of its appropriate track simultaneously, it has proved necessary to provide a means for changing the location of the portion of the drum surface being read by an individual read head. This is accomplished by mounting the lens in such a manner that the optical axis of the system is parallel to, but displaced from the mechanical axis of the cylinder. A small rotation of the cylinder will then move the lens in an arc which will carry it several bits along the length of the track while moving it but a short distance across the track. Because of the form factor of the individual bit, this system provides adequate adjustment.

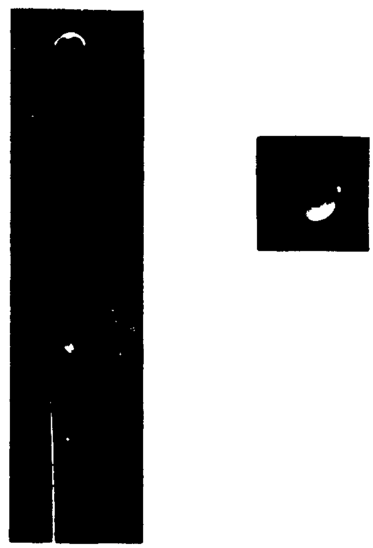


Figure 15 PLANO-CONVEX SAPPHIRE LENS

Because the sensitive area of the photodetector used is .008" by .028" or some 10 times the width of the bit being read, it is necessary for maximum efficiency to provide in the optical system a magnification of 10. This will insure that the size of the image of the bit is the same size as the sensitive area of the diode, thereby giving the maximum signal to noise ratio. Because of mechanical tolerances, etc. it was deemed advisable to provide a safety factor by making the image somewhat larger than the actual size of the sensitive area and hence a magnification of 12 was provided, as a reduction in the size of the bit image due to changes in the length of the optical path would result in a failure to resolve adjacent bits.

In order to focus the lens properly, shims are placed under the flange until the lens to drum distance is correct to give an image of the desired size at the desired location. This is normally not done visually but is done by placing a photodiode preamplifier combination in the read head and examining its output for the optimum wave shape (Figure 16).

The optical alignment of the photodiode and the optical properties of the photodiode will be discussed in the next section. Several possible methods of placing several diodes behind a single lens were considered. For example - one large lens looking at the entire drum surface with all 256 diodes behind it, or one lens looking at a portion of the drum surface and having 5 diodes behind it. It was known, however, that the diode was extremely sensitive to angular misalignment and that the angular misalignment could give rise to phase shift (Figure 16). For this reason, the above schemes were rejected as demanding too rigid mechanical tolerances and each read head was provided with its own lens.

The present system of holding the lens is not satisfactory on several counts. In the first place, it does not provide adequate means for aligning the diode angularly so that the sensitive area, which is randomly oriented with respect to the diode envelope, is perpendicular to the optical axis. Second, the cross track and the along track adjustments are mutually dependent and, third, the fact that the read heads are mounted and secured in pairs makes the adjustment of one of a pair without moving the other extremely difficult. A new design is under way to provide greater flexibility in the mounting area and also to provide the separate adjustments that are needed.

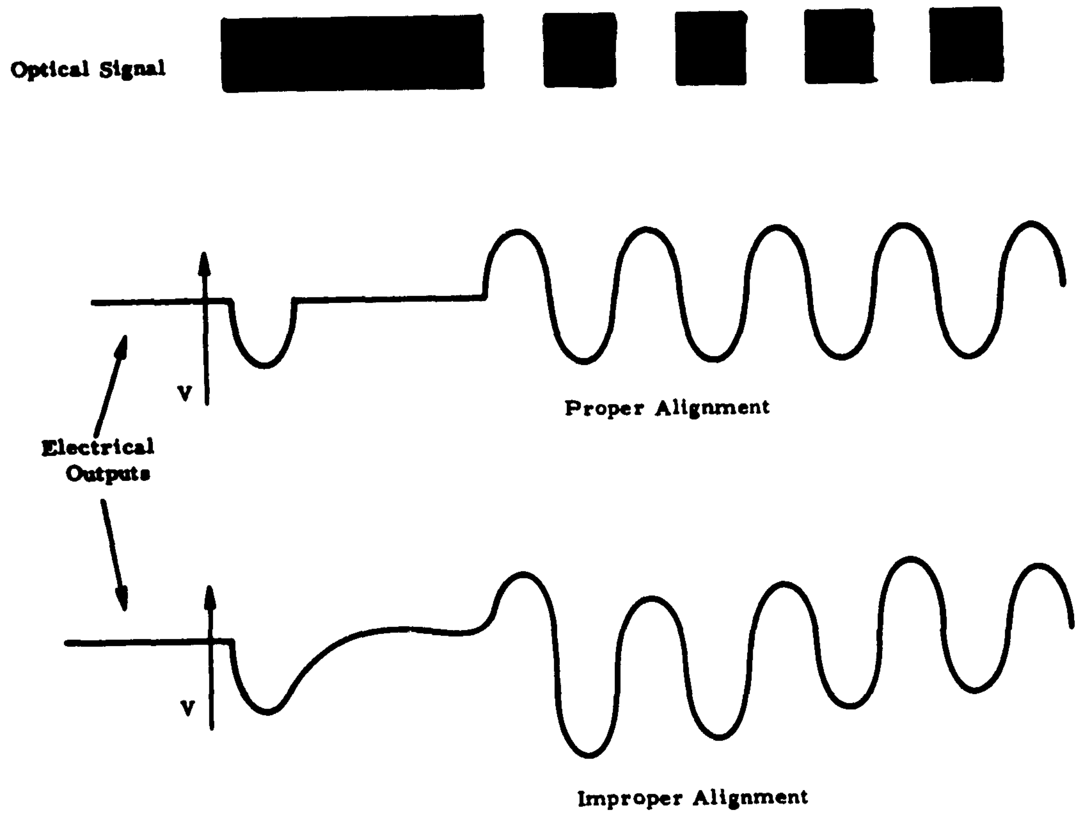


Figure 16 - Effect of Alignment on Electrical Outputs

2.6 Photodiode and Preamplifier

The photodiode preamplifier combination used is the Texas Instrument 1N2175 silicon photoduo diode and tuned preamplifier developed at Eclipse-Pioneer. This is packaged in the shape of a small flat segment of a circle with the photodiode protruding from the front end along the radius of the circle. (Figure 11). At the back, three terminals are provided for power, signal and ground. The circuit of the electronic system associated with a single channel is given in Figure 12. The preamplifier portion of this is made of miniature purchased components packaged on a thin printed circuit board. The photodiode is soldered to the preamplifier and held by a nylon sleeve glued to the board to give it mechanical support. The entire unit is covered with potting compound (PS 269). Adjustment is provided by moving the photodiode by bending its leads inside the nylon sleeve until suitable alignment has been achieved. The front end of the unit is supported by the nylon sleeve which fits under the back end of the lens mounting cylinder and the rear end support is provided by a metal strip which fits under the center terminal which is grounded. This strip is common to 5 pre-amplifiers and is secured to the circular plates at the top and bottom of the cylinder by screws. Before the photodiode is mounted, the spherical surface of the front end of the photodiode is ground flat, improving the optical properties considerably as the spherical end is merely a flame polished seal.

Because of the form factor of the sensitive area of the photodiode, it is necessary to see where the long axis and the short axis of the sensitive area are, and to orient the photodiode with respect to the amplifier so that in the final unit, the long axis will be parallel to the drum axis.

The photodiode is then placed in the tube at such a distance that the image will be in focus. If the image size is too small, more than 1 bit in the case of NRZ coding or 1 bit and a portion of the dividing space in the case of RTZ coding will fall on the sensitive area simultaneously. This will cause not only a diminishing of signal, but may also cause some apparent phase shift. It is important then that the size of the image be no smaller than the size of the sensitive area.

The maximum size which may be used is determined by the intensity of light that falls on the photodetector. This intensity must be sufficient to give an adequate "signal to noise" ratio. Since the noise level is generally independent of bit size, the signal to noise ratio is determined by the light intensity and hence is proportional to the inverse square of the magnification provided.

One of the difficulties encountered in this class of device is the reduction of the noise level to a point where a suitable magnification can be found which is large enough to provide adequate optical resolution and yet not so large that the signal intensity is unusably low. This reduction requires most careful attention to grounds and power supplies and, in addition the production of an adequate signal requires the utmost care in the optical alignment of the system to insure that there is minimum light loss.

In the course of investigation, it also appeared that one of the determining factors in the speed of a photodetector is the size of the area irradiated. (This appears to be related to the diffusion rate of the carriers but no satisfactory explanation has been found) For this reason, an attempt to slit the diode, that is to place an optical stop in the light path so as to reduce the effective size of the image, was attempted. Although, theoretically desirable, the practical difficulties of aligning a slit rendered this unusable

Several different classes of photodetectors were evaluated - none of which were satisfactory. This includes the Texas Instrument 1N2175 and other detectors whose characteristics are summed up in Table III. All of them were much slower than the megacycle read out rate desired and many of them were unusably slow. The selection of the 1N2175 was based largely on the fact that it is a silicon detector and hence less temperature sensitive than germanium, cadmium sulfide or lead sulfide. Another criterion was the physical package in which this detector came which was already amenable to the type of package envisioned. Several photodetectors have appeared since the evaluation of this detector which show better electro-optical characteristics, however, they are not available in a form which would be suitable for incorporation into this device.

A curious anomaly has been observed in the functioning of the 1N2175. This device is a duodiode, that is to say, two photodiodes

TABLE III

RISE AND FALL TIME OF SELECTED SILICON AND GERMANIUM PHOTODIODES (ALL TIMES IN MICROSECONDS)

Diode	T_{rise}	T_{fall}
1N77B (Ge)	.4	5
1N2175 (Si)	.4	5
FSP 166 (Si)	.3	5
FSP 55 (Si)	.3	3
7223 (Ge)	.5	5
Light Source	.1	.35

arranged in the same slab of material. Normally, only one of these junctions is active, that is to say, the biasing will only allow current to flow when a specific one of the junctions is illuminated. If the diode is swept with a bar of light as is the case of an optical memory, a significant difference in output is obtained depending on whether the pattern strikes the active or the inactive function first. The signal is about 40% improved by placing the active junction in the leading position. The cause of this is not understood.

Future work in this area involves close cooperation with manufacturers of semi-conductor detectors in order to obtain improved detectors, in a package which will be compatible with system requirements. Also, a redesign of the mechanical mounting to improve the ease with which the device may be adjusted and aligned is in process.

2.7 Electronic Circuitry

The system as delivered included a tuned preamplifier, high gain amplifier and a Schmitt trigger. The circuit of the unit is shown in Figure 12. This circuit will be discussed in detail below.

The major effort in the development program was devoted to extending the intrinsic high frequency roll off of the photodiode. The intrinsic break point (frequency at which the output of the diode began to decrease at 6 DB per octave) was approximately 15 KCPS. It was necessary, therefore, to provide sufficient compensation in the electronic circuitry to avoid amplitude degradation and phase shift due to poor high frequency response.

A linear circuit model for the photodiode was established. This consisted of a frequency sensitive current source shunted by a high impedence and a capacitor. Based on this model, the circuit of Figure 12 was ultimately designed. This model differs markedly from the equivalent circuit which is usually given, but appears to be more closely related to the actual item. This circuit functions in the following manner. As the drum rotates, alternately opaque and transparent areas sweep past the lens and their motion is imaged on the photodiode. As a transparent area is imaged on the photodiode, it is illuminated and produces an electronic current into the preamplifier. The preamplifier is tuned to pass only those frequencies of interest, thereby maintaining a useful signal-to-noise ratio while

providing gain in a predetermined frequency range. Input capacitance effects are minimized by the relatively low input impedance of the preamplifier. The amplifier signal is further amplified to a usable level where it can be shaped by the Schmitt trigger circuit.

For NRZ optical drum encoding, the tuned preamplifier is used with sufficient overcompensation so that the electronic output is essentially the derivative of the optical pattern on the drum. Therefore, changes in optical level are read rather than the levels themselves (Figure 17). The final stage, in addition to clipping and squaring, acts as a memory restoring the DC component of the original signal that was lost during the first stage of amplification.

2.7.1 Circuit Description

a) Tuned Preamplifier

The preamplifier resembles a standard shunt-peaked stage. However, a normal shunt-peaked stage forms a tuned circuit from collector to ground. In this circuit, the collector impedance remains inductive over the frequency range of interest, and the tuned circuit is formed in the base circuit by means of the reflected impedance of the Miller capacitance (collector to base). This arrangement allows two frequency sensitive circuits: a tuned citcuit in the base, and an inductance in the collector. The rising response (with increasing frequency) of the inductor essentially cancels the inherent roll-off of the photo detector current source, and the tuned circuit peaks at approximately 1 MC to provide usable signal from 50 KC out to 1 MC. Figure 18 shows the frequency response of the photodiode and preamplifier individually and in cascade.

The signal is then fed through an emitter follower (a standard buffer stage) to prevent loading on the inductor and provide a low impedance source to the succeeding amplifier stages.

b) High Gain Amplifier

The high gain amplifier, connected to the output of the buffered preamplifier, has a nominal gain of 500 over a relatively wide frequency range (30 KC to 1.7 MC). This amplifier utilizes voltage

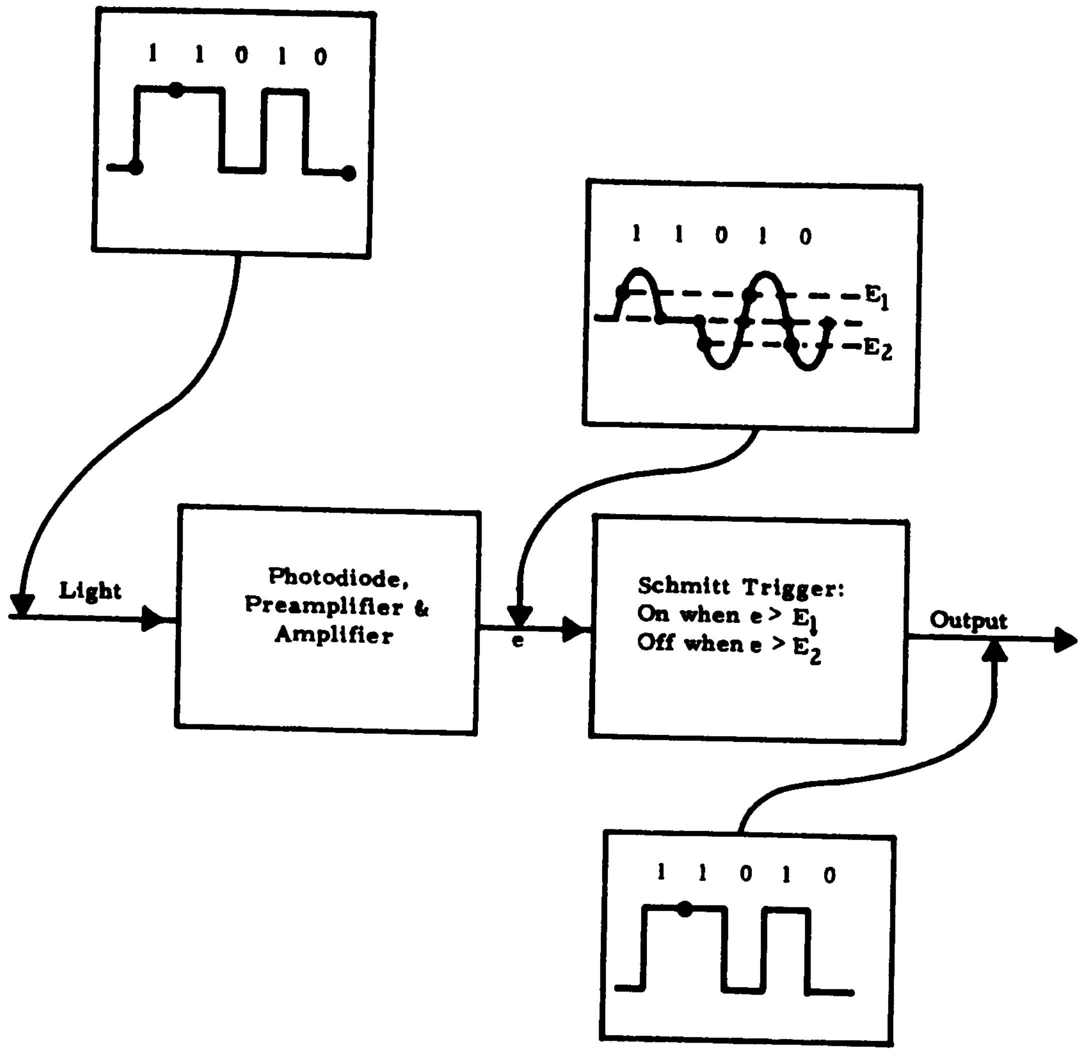


Figure 17 - NRZ System

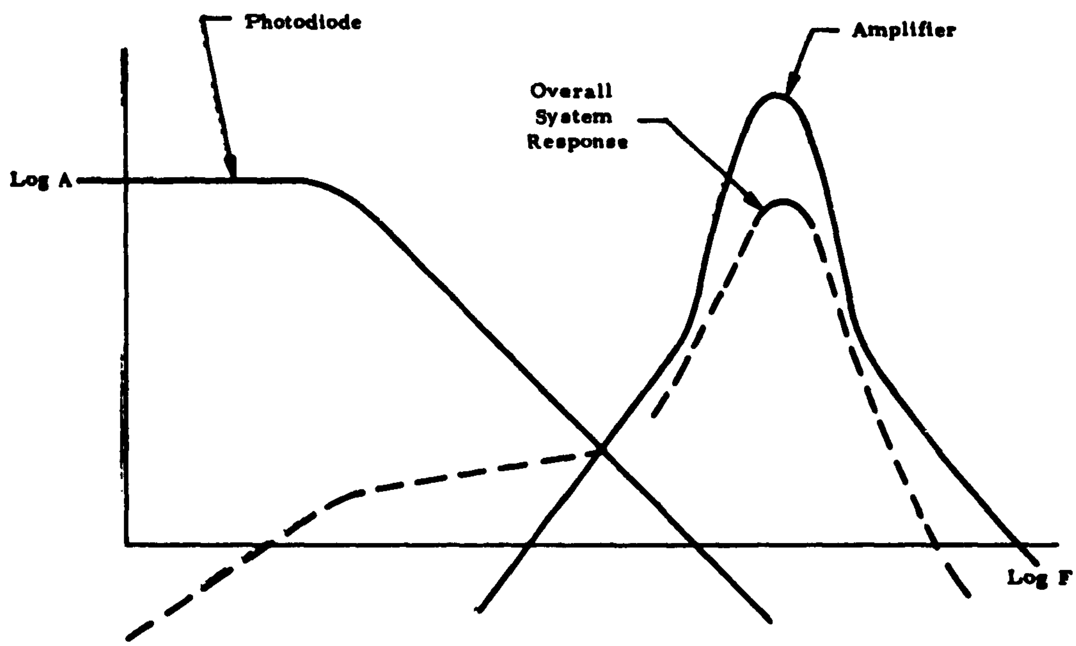


Figure 18 - Tuned Preamplifier, Frequency Response

feedback for bias stabilization. The circuit configuration is a standard one; the use of extremely low feedback resistors is an unusual feature. The feedback resistances are chosen to provide a design compromise between high gain and high frequency roll off.

It was mentioned previously that overcompensation is provided so that the output of the high gain amplifier is the derivative of the input light signal. This overcompensation is provided by the steepness of the tuned circuit response in the preamplifier, and by suitable adjustment of the coupling capacitors in the high gain preamplifier. The net result is an output signal that responds to changes in light signal, and thus, at this point the DC level of the original NRZ coded signal has been lost. In order to recover the DC level, and to shape the actual waveform, This output is then fed to a Schmitt Trigger.

c) Schmitt Trigger

The Schmitt circuit is designed to trigger or set on a positive level and reset on a negative level (Figure 17). The emitter coupling resistor sets the dead zone or hysteresis width of the circuit while the potentiometer allows for manually setting the level at which the circuit will fire.

The hysteresis is set at approximately 0.5 volts so that noise signals of this magnitude will not effect the output waveform. The input signals to the Schmitt trigger should be at least 1 volt peak-to-peak.

This was not the only approach taken. The first approach was to develop a high impedance preamplifier using bootstrapping techniques to minimize capacitiveeffects which would produce a frequency roll-off of the same magnitude as the inherent degeneration of the diode. Compensation was then added which in effect extended the useful frequency range of the photodiode. The AC equivalent circuit of this arrangement is shown in Figure 19. This initial approach to the electronic system proved moderately successful but would not have sufficient high frequency response to give adequate performance in the desired system.

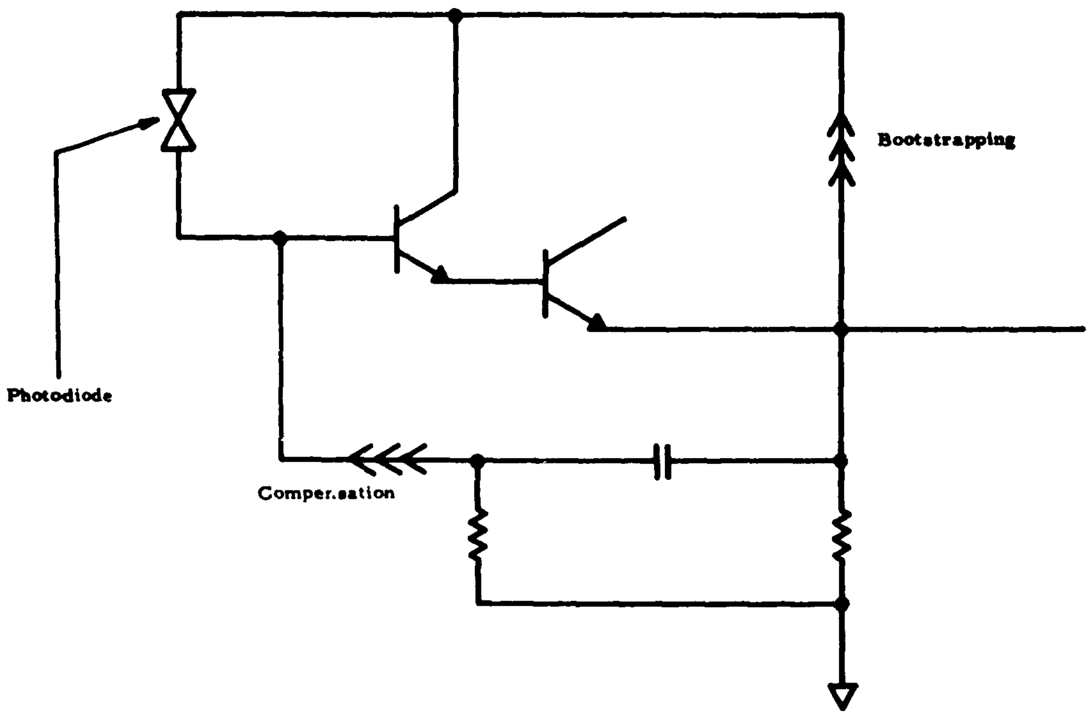


Figure 19 - Emitter Follower Preamplifier AC Equivalent Circuit

2.7.2 Packaging

It was found, experimentally, that some packaging precautions were required to insure reliable circuit operations. The problems noted were: uncontrolled oscillation, excessive pick-up and cross-talk.

Careful decoupling of power supplies as close to the circuit as possible alleviates the oscillation and cross-talk problem; power supply bypass capacitors are used at each preamplifier, amplifier, and Schmitt trigger. Also, a solid ground bus is necessary to reduce noise and prevent oscillation. Note that a spurious voltage spike will cause an erroneous output that may last for many bit times.

The preamplifier and photodiode are packaged together in order to reduce lead length between the detector and preamplifier, thus further reducing noise and pick up. Coaxial cable is used for interconnecting the output of the preamplifier to the input of the high gain amplifier and for connecting the B+ point of the preamplifier to the B+ point of the high gain amplifier. The coax shield must be grounded at only one end.

2.7.3 Maintenance and Operation

The alignment of the photodiode relative to the drum is very critical. If electronic signals at the output of the amplifier are not greater than 1 volt, a check should be made of both the optical alignment and light intensity of bulb before attempting an electronic check of the preamplifier and/or amplifier. A rapid test for catastrophic failure of the photodiode-preamplifier-amplifier subsystem may be performed by using a light pulse source (e.g. "Strobotac" by General Radio) shining directly into the photodiode; a very large electronic output should result.

2.8. Display Circuitry

Additional display circuitry not called for under the contract was built to illustrate the actual operation of the optical memory in a digital computer. Owing to the high noise level developed in the

prototype it is not possible to use this circuitry to clearly illustrate the functioning of the unit. Should the noise level be reduced to that expected in a flyable system, however, this circuitry would allow the operation of the memory to be monitored without the use of special equipment such as an oscilloscope, and would therefore, enable the functioning of the memory to be made clear to non-technically trained personnel.

The circuitry is designed to show two modes of operation, serial look-up and parallel readout. In each of these, an address is set in manually, and the data corresponding to that address is shown on an array of lights.

In each case the address is set in by throwing switches. Upon pressing the "reset" button, the display counter is cleared, a control FF is reset, and the next subsequent pulse from the "start" track transfers the number from the switch array into an address counter (upper portion of Figure 20). Pulses are then fed into the address counter from the "clock" track. When this counter crosses "zero" it emits a signal which stops itself from counting and is used to initiate the readout display. Meanwhile, the control FF has been set so that no further start action ensues.

In the serial look-up mode, the contents of an incremental data track are counted into the display counter. An incremental data track has pulses spaced in even differential changes of value of a function so that after a number of pulses, x, have been counted in the clock track, a different number of pulses, f (x), has been counted in the incremental track.

In operation, the serial look-up system operates as follows: (Figure 20) - an address is set into the switches and the display counter is cleared by pressing the reset button. Upon the arrival of the next "start" pulse, pulses are gated from the clock track into the address counter, and from the incremental track into the display counter. After the address counter crosses zero, and stops pulses from entering, pulses are also stopped from entering the data counter. The contents of the display counter are indicated on the light panel.

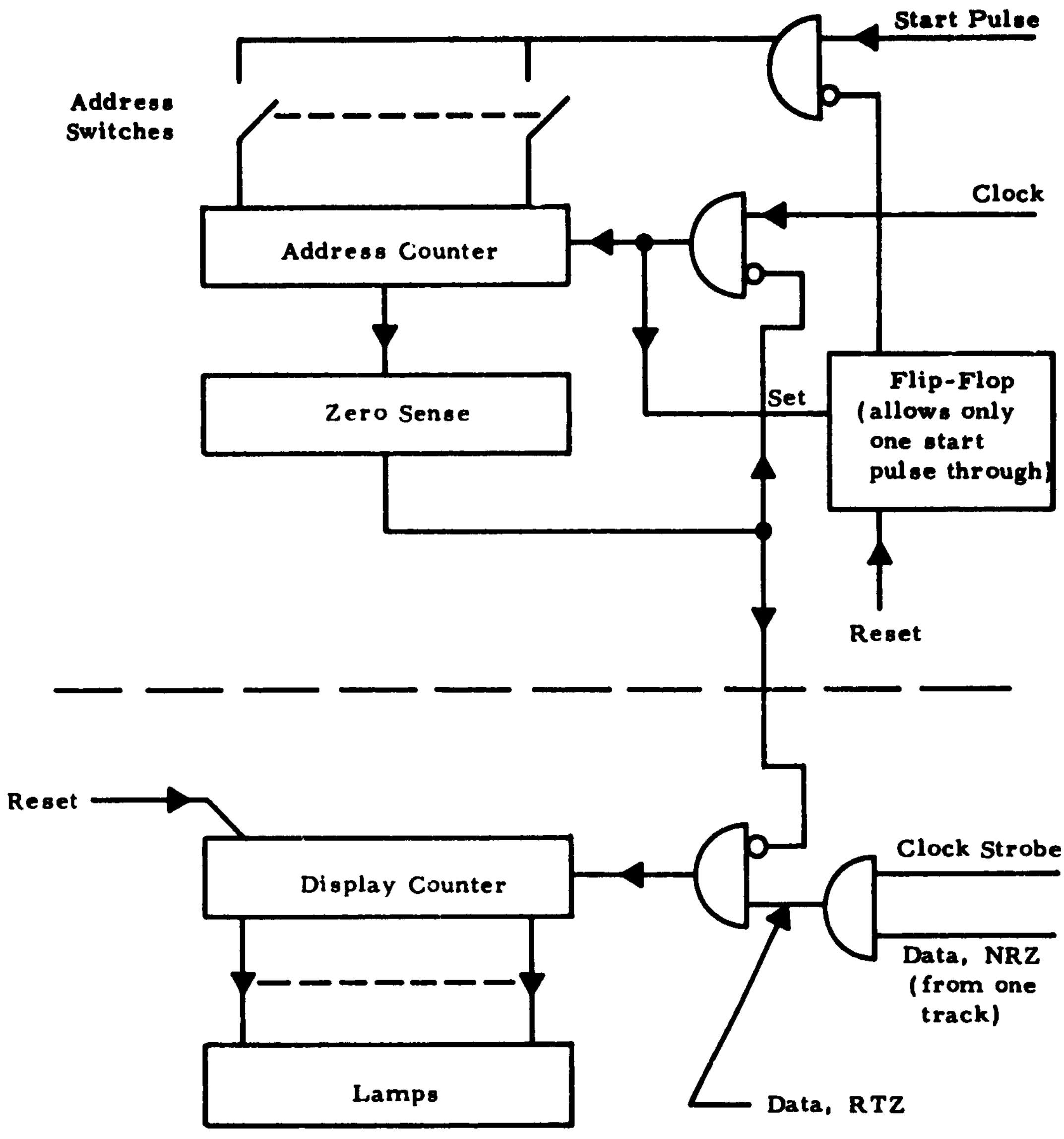


Figure 20 - Block Diagram-Serial Look-Up

In the parallel display mode, (Figure 21), the zero crossing of the address counter activates a series of gates which displays the readings of the various read heads at the instant of transition, on the light panel.

The two modes of operation of the display circuitry highlight the two main uses of the optical memory. For program or fixed constant storage in a parallel general purpose computer, the parallel mode is utilized. The address of the desired word is set into the address register; when the drum has rotated to the correct position, a word is instantaneously read from the drum. The number of bits in this word corresponds to the number of tracks on the drum.

For a serial general purpose computer or for a special purpose computer, the serial mode is utilized. The bits in a single track are observed and are either counted or routed to a program decoder depending on whether the track contains data or program words.

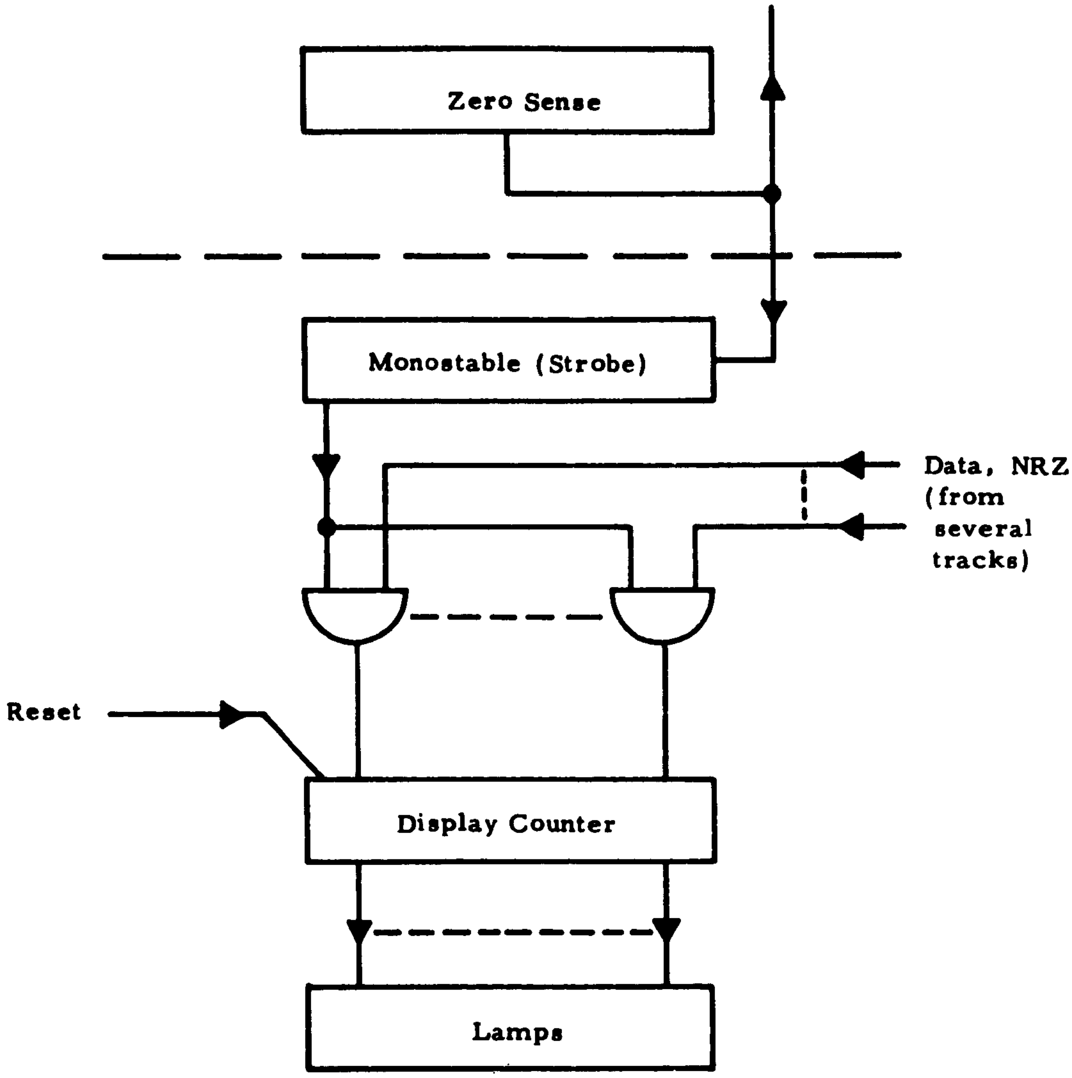


Figure 21 - Block Diagram - Parallel Display

SECTION 3

SUMMARY AND RECOMMENDATION FOR FUTURE WORK

This report concludes the work on the subject contract. Further work will be continued in this field by the Bendix Corporation, Eclipse-Pioneer Division, at its own expense, to incorporate the experience gained in this contract into future units.

Taking the unit subsystem by subsystem, the illumination fixture is at present far from satisfactory and work is continuing in the development of fiber and reflective optical systems. (Section 2.1) Work will also be undertaken with advanced types of bulbs.

The drum manufacturing system is having several changes made to incorporate changes in the state of the art in data handling, light sources, etc. In addition, in order to decrease the rate of mechanical failure, the mechanical shutters are being replaced with solid state shutters. (Section 2.2)

The drum coating is satisfactory with present line density but new techniques are under investigation in order to increase the information capacity of the drum. (Section 2.3)

In the motor, the only change envisioned is sealing to increase reliability. (Section 2.4)

The optical system is the area of a major redesign to provide greater alignment capability. (Section 2.5)

The photodiode is unsatisfactory and will be replaced as soon as a commercially available photodiode meeting our requirements is found. (Section 2.6)

The electronics perform well, however, a redesign to eliminate the inductor is desired in order to reduce the overall package size. This will also enable microcircuitry to be used. (Section 2.7)

The application of this and similar devices appear widespread in the computing and control system field and will be of material benefit to any future programs.

Aeronautical Systems Division, Dir/Avionics, Electronic Technology Lab, Wright-Patterson AFB, Ohio.
Rpt No. ASD-TDR-62-791. HIGH DENSITY OPTICAL MEMORY DRUM. Final report, Feb 63, 49p. incl illus., tables.

Unclassified Report

This paper discusses the techniques of manufacture of high density permanent storage devices for digital computers using optical techniques. The application of these techniques is shown in a feasibility model delivered to the Air Force under the subject contract. This memory had a storage capacity of over a million bits and occupied approximately 1/8 cu. ft. The experimental results are given and future

(over)

plans are outlined.

1. Digital computers
2. Storage devices
3. Memory devices
4. Optical memory devices

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II. Contract AF33(616)-7995
III. The Bendix Corporation Eclipse-Pioneer Div., Teterboro, New Jersey
IV. Dr. W. W. Lee
V. Aval fr OTS
VI. In ASTIA collection

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